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## NEUTRINO PHYSICS EXPERIMENTS

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# Neutrino Physics Experiments

William C. Louis, III

## Abstract

This LDRD project performed research and development in some advanced technology areas that significantly enhanced and broadened the performance of the Booster Neutrino Experiment (MiniBooNE) at Fermilab and the Sudbury Solar Neutrino Observatory (SNO) experiments. These experiments are well-poised to resolve the Liquid Scintillator Neutrino Detector (LSND) and solar neutrino anomalies and are capable of proving that neutrino oscillations occur and of making precision measurements of the neutrino oscillation parameters. These explorations may well provide answers to some of the most basic questions in fundamental physics that remain unresolved in our understanding of the universe.

## 1. Background and Research Objectives

### A. MiniBooNE

The LSND experiment at the LANSCE accelerator facility has obtained strong evidence for neutrino oscillations. Using neutrinos from  $\mu^+$  decay at rest, LSND has observed an excess of  $87.9 \pm 22.4 \pm 6.0$  events that are consistent with anti-muon neutrino to anti-electron neutrino oscillations. Combining this result with limits from other experiments, the oscillation probability is approximately 0.26% and the most favored mass range is from 0.2 to 2.0  $\text{eV}^2$ , implying that at least one neutrino has a mass greater than 0.4 eV and that neutrinos contribute more than 1% to the mass of the universe. It is difficult to explain the LSND neutrino oscillation evidence with only the three standard neutrinos together with the oscillation evidence from solar and atmospheric neutrinos. This difficulty implies new physics beyond the standard model, such as sterile neutrinos or CPT violation. As the only oscillation evidence from an appearance accelerator experiment, it has become imperative to mount a new experiment that will test in a definitive manner the LSND results.

Motivated by the LSND results, the Booster Neutrino Experiment (MiniBooNE) is nearing completion to run at Fermilab. MiniBooNE will make use of the 8 GeV proton Booster accelerator, which is capable of running at 15 Hz, although only 5 Hz is required for the remaining Fermilab program. Therefore, MiniBooNE will be able to run independently of other programs at Fermilab. The MiniBooNE detector consists of a sphere 40 feet in diameter that is located 500 m from the neutrino source. The detector is covered by 1520 phototubes (1220

phototubes and the electronics are from the LSND experiment) and filled with 800 tons of mineral oil. Extensive Monte Carlo simulations have demonstrated that electrons can be distinguished from muons and neutral pions, so that the total background is at the 0.5% level and a sensitive search for  $\nu_\mu \rightarrow \nu_e$  oscillations can be performed. The MiniBooNE sensitivity to neutrino oscillations will be an order of magnitude better than the LSND experiment after 1 year of data taking and will fully cover the entire LSND region at the  $>5$  sigma level. Furthermore, if neutrino oscillations are indeed observed, then MiniBooNE can make a precision measurement of the  $\Delta(m^2)$  and  $\sin^2(2\theta)$  oscillation parameters with a  $\Delta m^2$  resolution of  $0.1 \text{ eV}^2$  after one year of operation.

## B. SNO

During the past 35 years, solar neutrino experiments have been carried out in parallel with detailed Standard Solar Model (SSM) predictions of the solar neutrino flux and energy spectrum. Radiochemical experiments exploiting Ga as a neutrino target (SAGE and GALLEX) provide an integral measure of the solar neutrino flux, including the low energy and predominant pp flux, the intermediate energy  $^7\text{Be}$  flux, and the higher energy  $^8\text{B}$  flux. Similarly, the pioneering Chlorine experiment provides an integral measure of the  $^7\text{Be}$  and  $^8\text{B}$  fluxes. The water Cerenkov detectors (K, SK, and SNO) measure directly the higher energy  $^8\text{B}$  flux. In all cases, terrestrial experiments measure a deficit of solar neutrinos relative to predictions of the SSM, and this deficit appears to be energy dependent. The SSM is constrained by knowledge of the solar luminosity and is now well-tested by helioseismology. The neutrino data is inconsistent with a model of the Sun that shines due to nuclear fusion and the standard model of nuclear and particle physics. This has formed the basis of the Solar Neutrino Problem and for many years has provided a tantalizing hint that neutrinos have mass and that mixing occurs in the lepton sector. Such phenomena, if proven by experiment, would mark the first departure from the standard model with profound implications for the fields of astrophysics, cosmology, and elementary particle physics. Modern experiments are thus designed to directly search for the physics manifest by neutrino oscillations where the interpretation of the experimental data does not rely upon SSM calculations for their interpretation.

The Sudbury Neutrino Observatory (SNO) is a 1000 tonne, heavy water, imaging Cerenkov detector operating 6800 feet underground in the Creighton Nickel Mine near Sudbury, Ontario, Canada. The SNO project is an international endeavor with collaborators from Canada, the United States, and the United Kingdom. With deuterium as the neutrino target, the SNO detector provides a unique signature for  $^8\text{B}$  solar neutrinos that allows for a SSM independent

resolution of the Solar Neutrino Problem. The charged current (CC) interaction of electron neutrinos on deuterium creates a relativistic electron that subsequently produces Cerenkov radiation that is detected in an array of some 10000 photomultiplier tubes. The CC interaction provides a good measure of the energy of the incident neutrino, as well as some directional information, and is sensitive only to electron neutrinos. The neutral current (NC) interaction proceeds with equal probability by all active neutrino flavors to produce a free neutron in the heavy water. Since the Sun can produce only electron neutrinos, a measure of the CC and NC interactions in SNO can provide direct evidence for solar neutrino oscillations. If the solar neutrino deficit is a result of electron neutrinos born in the Sun being converted to muon and/or tau neutrinos (so far undetectable in pre-SNO solar neutrino experiments), then the CC channel in SNO would observe a flux deficit while the total flux observed via the NC channel would remain intact. In addition, the SNO detector is sensitive to neutrinos through the elastic scattering (ES) of neutrinos from electrons, a channel that is mainly sensitive to electron neutrinos but that is also partly sensitive to muon and/or tau neutrinos. Consequently, a measure of the NC/CC and ES/CC ratio of solar neutrino interaction rates in SNO provides a SSM independent test of solar neutrino oscillations.

Construction of the SNO detector began in the early 1990s. Upon the completion of full scale construction and after a short commissioning phase, the detector became fully operational in 1999. Using event energy, position, and direction of our first neutrino observations in SNO, we successfully demonstrated that, in the region of interest, our signal is dominated by 8B solar neutrinos detected via the CC and ES interactions and that radioactive backgrounds are at acceptably low levels to determine the 8B flux via all three (CC, NC, and ES) reactions in SNO[2]. Based upon data accumulated over 241 live days between November, 1999 and January, 2001 we published our first solar neutrino physics result, namely a measurement of the CC interaction of 8B solar neutrinos on deuterium. The analysis was performed with a conservative high energy threshold and tight fiducial volume so as to make radioactive backgrounds and the NC signal negligible. We found that the 8B flux derived from the interaction rate in SNO to be  $(1.75 \pm 0.15) \times 10^{11}$  neutrinos/cm<sup>2</sup>/second, confirming the deficit of electron neutrinos detected at Earth relative to the SSM prediction of  $(5.05 \pm 0.91) \times 10^{11}$  neutrinos/cm<sup>2</sup>/second. The CC flux measured in SNO is also low relative to the ES flux determined to high precision in the SuperKamiokande (SK) experiment of  $(2.32 \pm 0.09) \times 10^{11}$  neutrinos/cm<sup>2</sup>/second. The difference in the 8B flux derived from the ES and CC measurements is positive evidence that electron neutrinos born in the Sun do indeed oscillate into muon and/or tau neutrinos that contribute to the ES interaction rate but not the CC interaction

rate. Furthermore, when deriving the total 8B neutrino flux from these two measurements, we find  $(5.44 \pm 0.99) \times 10^{11}$  neutrinos/cm<sup>2</sup>/second, in very good agreement with SSM predictions. These results provide a resolution of the 35 year old Solar Neutrino Problem and evidence for mass and mixing in the solar neutrino sector.

## **2. Importance to LANL's Science and Technology Base and National R&D Needs**

This project investigated fundamental aspects of the Standard Model that appear inconsistent with observations. By supporting innovative science research at such basic levels, this project contributed in a fundamental way to the Laboratory's science and technology base and national R&D needs.

## **3. Scientific Approach and Accomplishments**

### **A. MiniBooNE**

LDRD/DR funding played a crucial role in enhancing and broadening the performance of the MiniBooNE experiment. An improved likelihood-based event reconstruction and particle identification made possible the reconstruction of the  $\pi^0$  mass with a resolution of 25 MeV and resulted in a lower neutrino background (two order of magnitude reduction of the  $\pi^0$  background) and a higher efficiency (50%) for the oscillation signal. This new event reconstruction was completed and installed in the Analysis Framework. Also, a new phototube mounting design was developed, allowing a single oil volume to house both the 1280 detector phototubes and the 240 veto phototubes with an opaque barrier separating the detector region from the veto region. All 1520 phototubes have been mounted and tested inside the tank and are performing well. Furthermore, a new scheme for performing the data acquisition and trigger system was developed that involves an array of personal computers running LINUX. This system is much less expensive and more flexible than a single multiprocessor computer, as used in the LSND experiment. The new data acquisition system was implemented and is operational. Finally, the conceptual design of a new analog front-end electronics system was completed. The new design has a different memory architecture with more FIFOs and no dual-ported memories. This should make the system less expensive and more reliable than the present electronics system.

### **B. SNO**

Collaborators at LANL provide a significant and vital role in the SNO project and cover essentially all aspects of the SNO experiment, including detector design and construction, detector commissioning, scientific direction and planning, detector Monte Carlo and data

processing, calibration sources, analysis of calibration data, measurement of systematic uncertainties, signal extraction, and interpretation of physics results. The significant achievement of obtaining the first solar neutrino physics results from SNO can be summarized as follows:

(1) The 8B solar neutrino flux derived from the SNO CC interaction rate is low compared to that derived from the SK ES rate. This marks the first direct, experimental evidence for a non-electron, active neutrino component in the 8B solar neutrino flux and that electron neutrinos born in the Sun are actively converted to muon and/or tau neutrinos. This is evidence for neutrino mass and mixing in the lepton sector and requires new physics beyond the standard model of elementary particles.

(2) We have for the first time experimentally determined the total flux of 8B solar neutrinos, and this flux is in agreement with predictions of the SSM. Consequently, the solar neutrino problem is resolved and we have further confirmation of a sound understanding of how main sequence stars shine.

In addition to these observations for solar neutrinos, we can now also make some definitive remarks regarding neutrinos in cosmology. By taking the solar neutrino evidence for neutrino oscillations together with that from the atmospheric neutrinos in SK and the experimental upper bound on the electron anti-neutrino of 2.3 eV from tritium beta decay, we now know that the sum of all active neutrinos is in the range from 0.05 eV to 8.4 eV. This lower bound means that neutrinos contribute at least as much mass in the Universe as do all of the stars. The upper bound means that the neutrinos cannot contribute more than about 18% to the closure density of the Universe, indicating that the dark Matter in the Universe must be exotic and not in the form of ordinary matter known to us. We have thus witnessed a revolution in neutrino physics with profound implications for astrophysics, cosmology, and elementary particle physics. Neutrino physics offers a window to new physics, and future programs envisioned for solar neutrino detection such as LENS, experiments at accelerators such as MiniBoone, and avenues to the detection of Dark Matter will be a vital and important component of the LDRD program.

### C. Theoretical Progress I

From a theoretical perspective, project objectives included developing a new understanding of neutrino masses and neutrino oscillation behavior and (see-saw model) Majorana neutrinos, consistent with solar, atmospheric and beta decay experimental results.

By combining LSND with other data, we were able to resolve the Tritium beta decay anomaly and the supposed conflicts between neutrino oscillation data sets in terms of pseudo-Dirac neutrinos. The result is “natural” in the technical sense and correlates long baseline

oscillations with particle-antiparticle transitions versus flavor-changing oscillations on shorter baselines. More recent atmospheric results do not prefer this solution, and so we investigated lower rank see-saw models as well, to see whether they could accommodate this newer data.

In particular, we studied a rank -one variation of the pseudo-Dirac neutrino mass matrix, which we found could be consistent with all current neutrino mass and oscillation experiments. We found that natural large amplitude mixing into sterile neutrinos persists and that, for a wide range of parameters, this mixing is promoted into the flavor sector. That is, large amplitude flavor mixing can be induced without texture zeros common to other approaches. Thus, this lower rank see-saw model is found to accommodate more recent data by forcing two pseudo-Dirac mass eigenstates into proximity and simultaneously amplifying the mixing between those two states.

Our extended analysis of neutrino mass mixing matrices included the effects of pseudo-scalar and tensor new weak interaction currents on experimental bounds for combinations of entries and strengths. The Tritium beta decay experimental anomalies have apparently disappeared, but our analysis pointed out that, at the current limits on the strength of nonstandard interactions, their interference effects and neutrino mass effects could be canceling in Tritium beta decay experiments. We communicated this danger to the experimental groups and described the revisions in their analyses necessary to overcome this uncertainty.

We also found, from all known experimental sources, only weak limits on the strength of interactions of sterile neutrinos. We determined the bounds on sterile mixing for experiments that reported their results as consistent with pure flavor mixing. These corrections allowed for 25% to 40% contamination of the quoted result, significantly improving the accuracy of the experimental statements.

Our theoretical collaboration continues to work on interpreting ultra-high energy cosmic rays in terms of Z-bursts induced by neutrinos on the cosmic neutrino background. Our contribution to this analysis is in the range of possible neutrino masses and the nature of the interactions. We also continue to examine recent high-energy neutrino scattering results for resolution of their marginal apparent inconsistency with previous results in terms of oscillations to sterile neutrinos and new structures for their interactions with quark flavors.

The LSND and KARMEN experiments give information on non-standard two-neutrino decays, in which one of the neutrinos is the anti-electron neutrino. Such decays violate the conservation of lepton family number (LFN), and therefore do not occur in the Standard Model (SM). For the branching ratios of decays, where the anti-electron neutrinos have the same momentum spectrum as the anti-muon neutrinos in the SM, an upper limit of  $1.16 \times 10^{-3}$  (90%

C.L.) was set by the KARMEN collaboration. This results rules out at the 90% confidence level the possibility that the excess  $e^+$  events in the LSND oscillation experiment is due to such muon decays. Earlier we investigated the above class of non-standard muon decays in left-right symmetric models, and in R-parity violating supersymmetric standard model (RMSSM). We found in both models that for L(total lepton number)-conserving decays, data on some other LFN processes set upper limits on the branching ratio that are stronger than the KARMEN limit by an order of magnitude. Subsequently, we investigated the decay modes that violate L. Our conclusion is that for such decay modes the branching ratios in the RMSSM can be of the order of  $10^{-3}$ . In the left-right symmetric models the L-violating muon-decays are also too weak. For the latter decays (for which the current KARMEN limit does not apply) constraints from the KARMEN and LSND experiments have not been deduced yet.

We also examined the neutrino-carbon reactions measured at LSND and KARMEN, and compared them with other weak interactions on carbon. The calculations were carried out within a large-basis shell-model framework, which included excitations up to  $4\hbar\omega$ . When ground-state correlations were included with an open p-shell, the predictions of the calculations were in reasonable agreement with most of the experimental results for these reactions. Woods-Saxon radial wave functions were used, with their asymptotic forms matched to the experimental separation energies for bound states, and matched to a binding energy of 0.01 MeV for unbound states. For comparison purposes, the reaction rates were also calculated for harmonic oscillator radial functions. Closest agreement between theory and experiment was achieved with unrestricted shell-model configurations and Woods-Saxon radial functions. For the  $\nu_\mu C \rightarrow \mu^- X$  decay-in-flight flux, we obtained a neutrino-absorption inclusive cross section of  $13.8 \times 10^{-40} \text{ cm}^2$ , in close agreement with the LSND result. For the electron neutrino absorption from the decay-at-rest flux we also found a cross section in close agreement with the latest LSND result.

SNO measures the interaction of  $8B$  solar neutrinos with deuterium in heavy water in charged-current (CC) interactions and neutral-current (NC) events. In both cases, the measured quantity has to be referenced to a theoretical expectation. The leading order contributions are well known and account for 95% of the neutrino-deuterium cross sections. Obtaining accuracy for the last 5% is the problem, and the most important contribution comes from radiative corrections.

We computed the radiative corrections for the CC reaction,  $\nu(e)+d \rightarrow p+p+e^-$ , and for the NC reaction,  $\nu(x)+d \rightarrow p+n+\nu(x)$ . Nonrelativistic kinematics were used for the hadrons, which considerably simplifies the calculations. The impact of radiative corrections on the

observables at SNO was mostly found to be negligible. Only in the case where the internal bremsstrahlung photons emitted in the reaction  $\nu(e)+d \rightarrow p+p+e(-)+\gamma$  are detected, was the expectation for the ratio of the number of CC to the number of NC events seen in SNO shifted by about one standard deviation.

The sensitivity of SNO to measure the shape of the recoil electron spectrum in the charged-current reaction of 8B solar neutrinos interacting with deuterium can be improved if the results of a 8Li beta-decay calibration experiment are included in the test. We calculated an improvement in sensitivity, under certain idealistic assumptions, of about a factor of 2, sufficient to resolve different neutrino-oscillation solutions to the solar-neutrino problem. We further examined the role of recoil and radiative corrections on both the 8B neutrino spectrum and the 8Li electron spectrum and concluded that the influence of these effects on the ratio of the two spectra as measured by SNO is very small.

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